Development of a Test Methodology for Single-Event Transients (SETs) in Linear Devices

Christian Poivey, *Member, IEEE*, James W. Howard, Jr., *Senior Member, IEEE*, Steve Buchner, *Member, IEEE*, Kenneth A. LaBel, *Member, IEEE*, James D. Forney, Hak S. Kim, and Arheindal Assad

***Abstract*—We present single-event transient (SET) test data on linear devices under many operational conditions in an attempt to understand the SET generation and characteristics. This is done in an attempt to define a low-cost conservative test methodology to characterize these effects.**

***Index Terms*—Bipolar analog integrated circuits, comparators, integrated circuits, ion radiation effects, laser radiation effects, linear circuits, operational amplifiers, radiation effects.**

I. Introduction

SINGLE-event transients (SETs) have been observed in linear microcircuits [1]–[5]. These transients can occur in operational amplifiers, voltage references, voltage comparators, and other linear devices. Additionally, certain anomalies in space instruments have been attributed to analog SETs [1], [6].

One of the characteristics of SETs is that their pulse widths and amplitude are influenced by the device bias conditions [5]. The characterization of SET in the bias condition of specific applications has helped us to understand and mitigate their adverse effects on space systems [6]. Linear devices are used in high quantities in space systems and with many different bias conditions. This makes this characterization methodology very expensive and time consuming.

A low-cost conservative test methodology is needed to characterize these effects. To this end, we have collected heavy-ion and laser test data on three linear devices (two voltage comparators and one operational amplifier) under many operational conditions in order to define the worst case SET characteristics of these devices. Data have been collected in such a way that a predictive method could result. A cost-effective predictive methodology requiring minimal test data can yield conservative SET rate estimates.

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C. Poivey is with SGT-Inc., and also with NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: cpoivey@pop500.nsfc.nasa.gov).

J. W. Howard, Jr., J. D. Forney, and H. S. Kim are with Jackson and Tull, Seabrook, MD 20706 USA, and also with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: cpoivey@pop500.gsfc.nasa.gov).

S. Buchner is with SFA, Largo, MD, and also with the Naval Research Laboratory, Washington, DC 20375 USA.

K. L. LaBel and A. Assad are with NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

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TABLE I
TESTED DEVICES

Type	Manufacturer	Function
LM139	NSC	Voltage Comparator
HS139	Intersil	Voltage Comparator
LM124	NSC	Operational Amplifier

TABLE II
VOLTAGE COMPARATOR, BIAS CONDITIONS

Power Supply (V)	V+ (V)	V- (V)	Pull-up resistor (kΩ)
+7/0	0	0.1, 5	5
	0.1	0	
	0.2	0.1	
	1	3	
	3	1	
	5	0, 4.9, 5.1	
+15/0	5	15, 5.1, 4.9, 0	
	0	0.1, 5	
	0.1	0	
	1	3	
	3	1	
+/- 5	1	0 to 0.9	5
	3	2 to 2.95	2.5, 5
+/- 7	1	3	5
	3	1	
+/- 15	9	8 to 8.9	

II. Tested Devices and Test Conditions

A. Tested Devices

The devices tested are described in Table I. These three devices have been chosen because they are widely used in NASA space programs. Therefore, the data collected would allow one to bound the worst case SET response for these devices.

An SET hardened version of the Intersil comparator is now available. The tested device is the previous version that is hardened to total ionizing dose but not to SET.

B. Bias Conditions and Test Setup

The test bias conditions for the voltage comparators are shown in Table II. Four different applications have been investigated for the LM124: voltage comparator, noninverting gain (x101), noninverting gain (x11), and voltage follower. The voltage comparator and noninverting gain applications are shown in Figs. 1 and 2, respectively. The different bias conditions considered are described in Tables III–VI.

The output of the device under test (DUT) is monitored with a digital oscilloscope. As soon as the DUT output exceeds a given trigger level (generally 500 mV), an SET is counted and

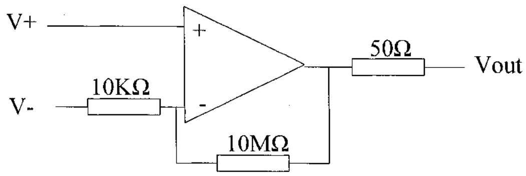

Fig. 1. LM124 voltage comparator application circuit schematics.

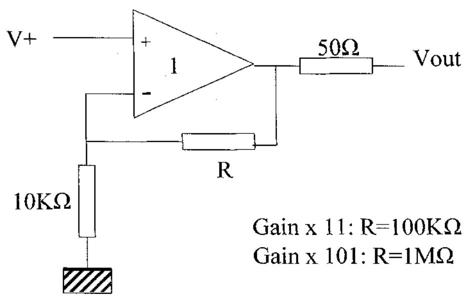

Fig. 2. LM124 noninverting gain application circuit schematics.

TABLE III
LM124 VOLTAGE COMPARATOR, BIAS CONDITIONS

Power Supply (V)	V+ (V)	V- (V)
+/- 15	0.05, 0.1, 0.3, 0.6, 1	0
	5.1, 5.3, 5.6, 6	5
	10.1, 10.3	10
	0	0.05
	5	5.1
	-5.1	-5
+5/0	2.9	3
	3	2.9, 2.95

TABLE IV
LM124 NONINVERTING GAIN x101, BIAS CONDITIONS

Power Supply (V)	Input Voltage (V)
+/- 15	0.05, 0.1
+ 5/0	0.015, 0.03

TABLE V
LM124 NON INVERTING GAIN x11, BIAS CONDITIONS

Power Supply (V)	Input Voltage (V)
+/- 15	0.1, 0.5, 1
+ 5/0	0.03, 0.15, 0.3

the complete SET transient data are stored on a computer for future analysis.

C. Irradiation Conditions

1) Heavy Ions: The voltage comparators were irradiated at the Brookhaven National Laboratory (BNL) Tandem Van de Graaff. The ions used are described in Table VII. The LM124 was irradiated at the Texas A&M cyclotron. The ions used are described in Table VIII.

2) Laser: The laser irradiations have been performed at the Naval Research Laboratory (NRL) laser test facility. The laser is a dye laser pumped by a YLF laser. The main features of the facility are presented in Table IX. The energy of the laser pulses could be varied with neutral density filters. During the experiments, the laser pulse rate was 100 Hz.

TABLE VI
LM124 VOLTAGE FOLLOWER, BIAS CONDITIONS

Power Supply (V)	Input Voltage (V)
+/- 15	1, 5, 10
+ 5/0	0.3, 1.5, 3

TABLE VII
TEST IONS USED AT BNL. NO TILTED BEAM HAS BEEN USED DURING THESE EXPERIMENTS

Ion	Energy (MeV)	LET in Si ($MeVcm^2/mg$)	Range in Si (μm)
O	130	2.6	143
F	142	3.4	122
Mg	165	6	86
Cl	215	11.4	65
Ti	230	18.7	48
Br	285	11.4	36
I	365	60	34

TABLE VIII
TEST IONS USED AT TEXAS A&M. IRRADIATIONS HAVE BEEN PERFORMED IN AIR. THE LET AND RANGE VALUES GIVEN IN THE TABLE ARE THE VALUES IN THE TARGET AFTER THE 25-mm ARAMICA BEAM WINDOW AND AN 8-cm DISTANCE OF AIR. OTHER LET VALUES HAVE BEEN OBTAINED BY TILTING THE BEAM

Ion	Energy (MeV/u)	LET in Si ($MeVcm^2/mg$)	Range in Si (μm)
Ne	15	2.9	246
Ar	15	9	162
Kr	15	30	108

TABLE IX
MAIN CHARACTERISTICS OF THE NRL LASER TEST FACILITY

Wavelength	590 nm
1/e penetration depth in Si	2 μm
Maximum energy	0.5 nJ
Pulse duration	3 ps
Spot size	1 μm (LM/HS139 experiments)
	5 μm (LM124 experiments)

III. TEST RESULTS

A. LM139&HS139

1) Heavy-Ion Results: All the transients have a similar shape: a sharp rise followed by an exponential decay. The polarity of the transients is determined by the input differential voltage δVi(δVi $=$ V+ $-$ V$-$). If δVi is positive, the transients are negative-going pulses. If δVi is negative, the transients are positive-going pulses. Maximum transient size is a power-supply rail-to-rail transient. At high linear energy transfer (LET) and low δVi, the transients are saturated, as shown in Fig. 3. The two devices showed a strong correlation between the input bias conditions and the SET sensitivity. Figs. 4 and 5 show the SET cross-section curves of the LM139 and the HS139, respectively, for the $\pm$5 V power-supply voltage condition. We can see in these figures that the smaller δVi is, the higher the SET sensitivity is.

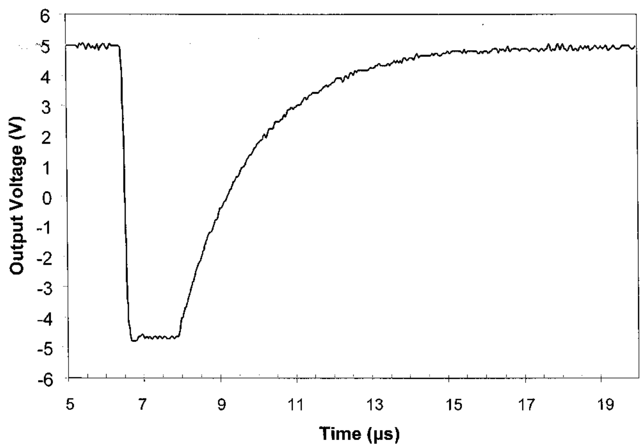

Fig. 3. HS 139, example of a saturated rail-to-rail transient.

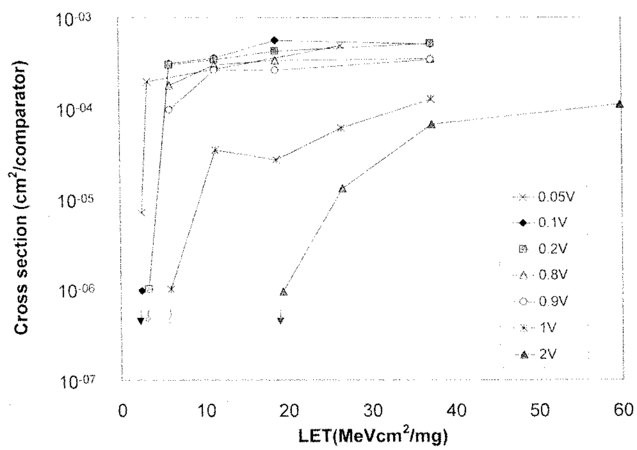

Fig. 4. LM139 cross-section curve for different values of δVi.

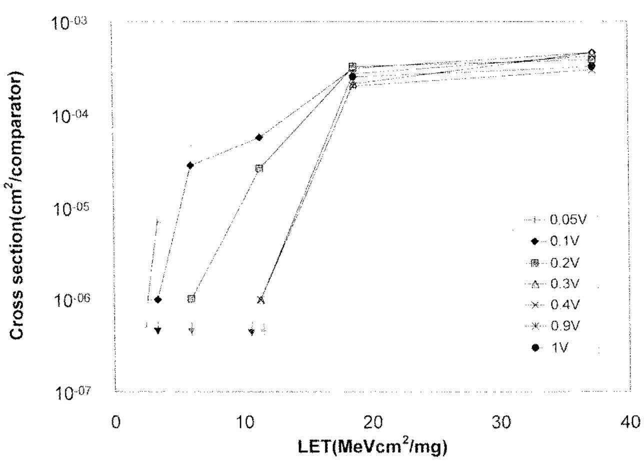

Fig. 5. HS139 cross-section curve for different values of δVi.

The differential input voltage has also a strong effect on the transient characteristics: the lower δVi is, the higher the peak amplitude voltage swing is. At low δVi, more than 90% of transients are rail-to-rail transients. Above a 0.7-V δVi, less than 50% of transients are rail-to-rail transients. Above a 1-V δVi, no transient is rail-to-rail. The LET also has a significant effect on the transient characteristics. Near the LET threshold, only a small number of transients are rail-to -rail transients, even for a low δVi. At high LET, transients are rail-to-rail and saturated.

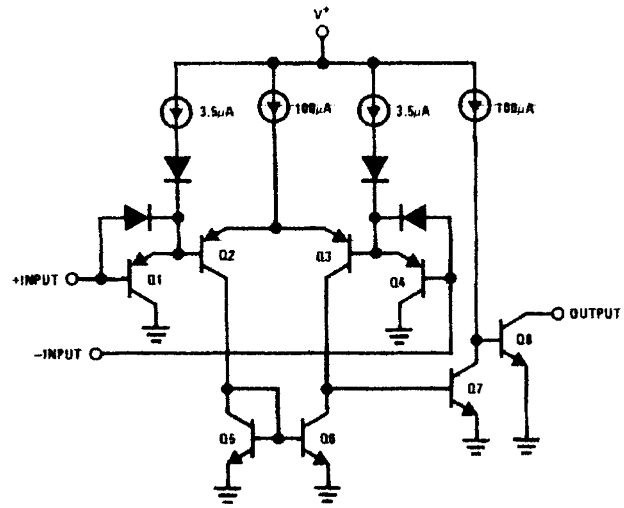

Fig. 6. LM/HS139 simplified circuit schematics.

The other test conditions are less significant. No clear effect of the power-supply voltage can be observed on the transient sensitivity. However, the power-supply voltage has an impact on the transient characteristics. A higher power-supply voltage gives a lower number of rail-to-rail transients. As expected, the value of the pullup resistor affects the transient duration but has no effect on the transient sensitivity.

2) Laser: A simplified LM/HS139 schematic is shown in Fig. 6. For both devices, laser irradiation has shown that the second stage of the input differential amplifier (transistor Q2 when δVi is positive and transistor Q3 when δVi is negative) is the most sensitive area. The input transistors Q1 and Q4 are also very sensitive for the LM139, but are significantly less sensitive for the HS139.

B. LM124

1) Heavy Ions: Unlike the LM/HS139 results, the LM124 results showed a large variety of transient waveforms and a significant impact of the power-supply voltage.

The LM124 exhibits a very low sensitivity when it is used as a voltage comparator. In the worst case condition (Vcc $=$ ±15 V and δVi $=$ 0.05 V), only one event was observed at the LET of 42 MeVcm^2/mg. At the 60-MeVcm^2/mg LET, the SET cross- section is 6×10^{-6} cm^2/amplifier. Of the transients, 99% are small positive-going (up to the +Vcc rail) transients. The maximum voltage amplitude is 2 V and the maximum full-width at middle-height (FWMH) is 100 ns. The remaining 1% of transients are large negative-going transients with a voltage amplitude larger than 10 V and a duration longer than 10 μs. The lowest δVi gives the highest SET sensitivity, but δVi has only a little effect on transient sensitivity. When the power-supply voltage is +5/0 V, the sensitivity is significantly lower. The SET cross-section at the LET of 60 MeVcm^2/mg is lower than 5×10^{-7} cm^2/amplifier.

The LM124 exhibits a higher SET sensitivity when it is used as a noninverting gain amplifier or a voltage follower. Fig. 7 shows

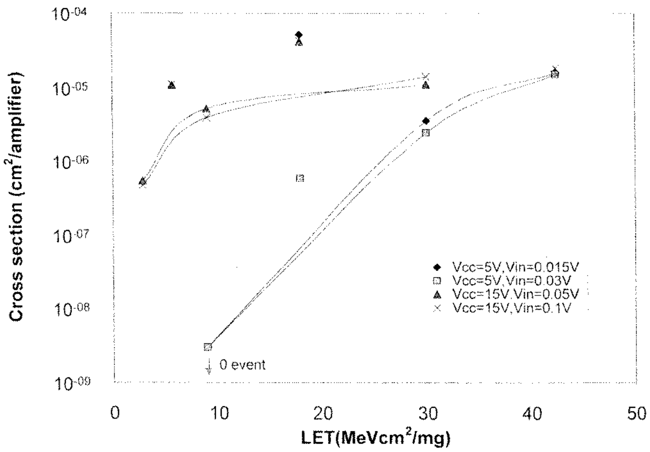

Fig. 7. LM124, noninverting gain x101 application, SET cross-section curve. The experimental points that do not fit the curve are tilted points. We can see that the cosine law for beam angle does not apply for this device.

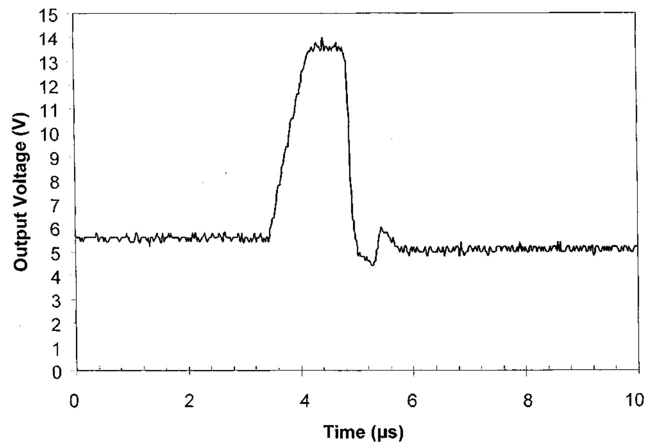

Fig. 8. LM124, noninverting gain x101 application, typical large bipolar transient at low LET. LET $= 2.86$ MeVcm^2/mg, Vcc $= \pm 15$ V, V+ $= 0.05$ V.

the SET cross-section curve for the noninverting gain of 101 application. The LET threshold is lower than 2.86 MeVcm^2/mg and the cross-section at the LET of 30 MeVcm^2/mg is 10^{-5} cm^2/amplifier. These worst case results have been obtained with a $\pm$15 V power-supply voltage for both input voltages investigated. The worst case cross-sections for a noninverting gain of 11 and the voltage follower applications are similar for the $\pm$15 V power-supply voltage, but we see an effect of the input voltage near the LET threshold. Near the threshold, the lower input voltages give the higher SET sensitivities.

When the power-supply voltage is +5/0 V, the SET sensitivity is significantly lower for high input voltages. In these conditions, no event has been observed at the LET of 9 MeVcm^2/mg and only a few events have been observed at the LET of 30 MeVcm^2/mg.

Three different types of transient have been observed.

1) Large bipolar transients that are predominant especially at low LET. The transient's negative-going component characteristics are very dependent on the application (the higher the gain, the lower the amplitude, duration, and power-supply voltage). The overall transient characteristics vary with the LET.
2) Long-duration positive-going transients that only appear at high LET and could represent up to 35% of the total number of transients.
3) Small positive-going transients that are marginal at low LET and could represent up to 25% of the total number of transients at high LET.

An example of a large bipolar transient is shown in Fig. 8. The transient's positive-going component goes up to the +Vcc rail and has a 1.5-μs FWMH. The transient's negative -going component has a less than 0.5-V amplitude. When the LET increases to 30 MeVcm^2/mg, the transient's positive-going component becomes smaller in amplitude and shorter in duration. When the application gain is lower, the transient's negative-going component becomes larger, as shown in Fig. 9 for the noninverting gain of 11 application. Its maximum voltage amplitude is 3 V and its duration is greater than 10 μs.

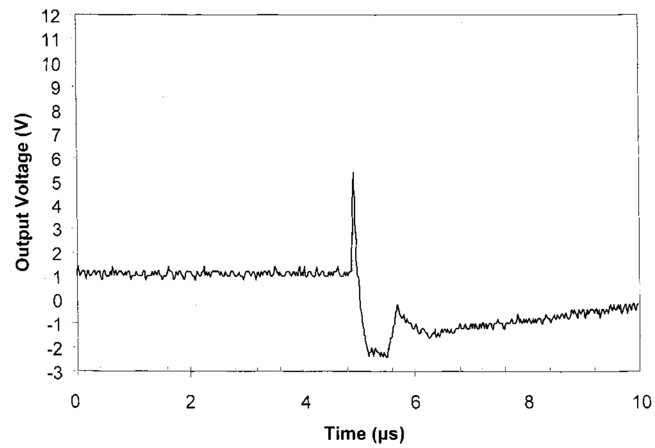

Fig. 9. LM124, Noninverting gain x11 application, large bipolar transient at high LET with a small positive-going component. LET $= 30$ MeVcm^2/mg, Vcc $= \pm 15$ V, V+ $= 0.1$ V.

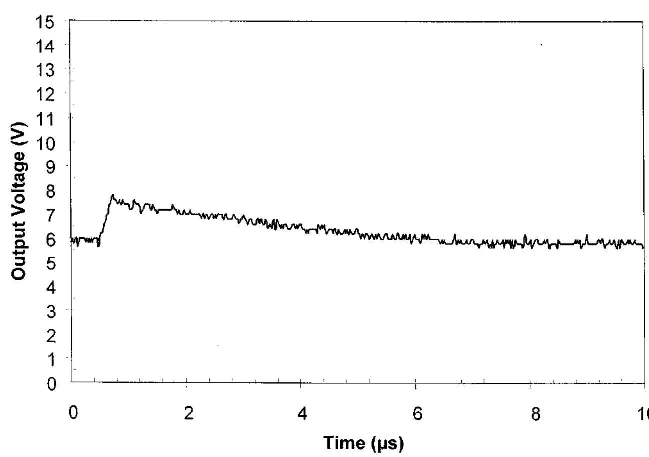

Fig. 10. LM124, noninverting gain x11 application, typical long-duration transient observed at high LET. LET $= 30$ MeVcm^2/mg, Vcc $= \pm 15$ V, V+ $= 0.5$ V.

The worst case amplitude of long-duration transients is 2 V and their maximum FWMH is larger than 10 μs. A typical waveform of a long-duration transient is shown in Fig. 10.

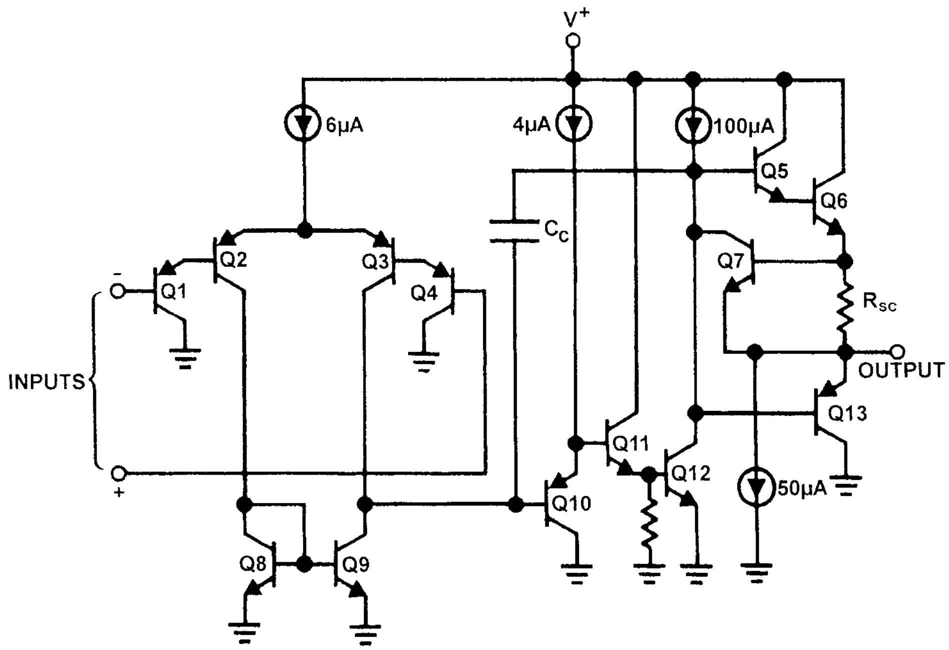

Fig. 11. LM124 simplified circuit schematics.

The worst case amplitude of a small transient is 2 V. The worst case FWMH is 600 ns.

Another result observed during these experiments is that the experimental points obtained with tilted angles do not fit the cross-section curves. This can be seen in Fig. 7. In other words, the effective LET concept is not valid for these devices.

2) Laser: A simplified LM124 schematic is shown in Fig. 11. Six sensitive areas have been identified. Some regions are not sensitive for some applications and are very sensitive for other applications. Depending on the bias conditions and laser energy, the transient size could change dramatically, but each sensitive region gives the same type of waveform:

1) Large positive-going or bipolar transient (positive-going and then negative-going): Q5/Q6 and 100-μA current source;
2) Small long-duration positive-going transients: Q8/Q9;
3) Large negative-going transients: Q12 and 4 μA current source;
4) Large negative-going transients or small bipolar transients (negative-going and then positive-going): Q11 collector.

Depending on the applications and bias conditions, all six sensitive regions could have a very low energy threshold, but regions Q5/Q6 and Q8/Q9 have a significantly larger area. A typical negative-going transient for the comparator application is shown in Fig. 12. This transient is obtained when the transistor Q12 is irradiated with a 64-pJ laser beam. A typical bipolar transient for the noninverting gain application is shown in Fig. 13. This transient is obtained when the transistors Q5/Q6 are irradiated with a 214-pJ laser beam. We can see that at this high laser energy, the negative-going component is significant: the voltage amplitude is 7 V and the FWMH is about 20 μs. When the laser energy is reduced, the amplitude of the transient's negative component is smaller.

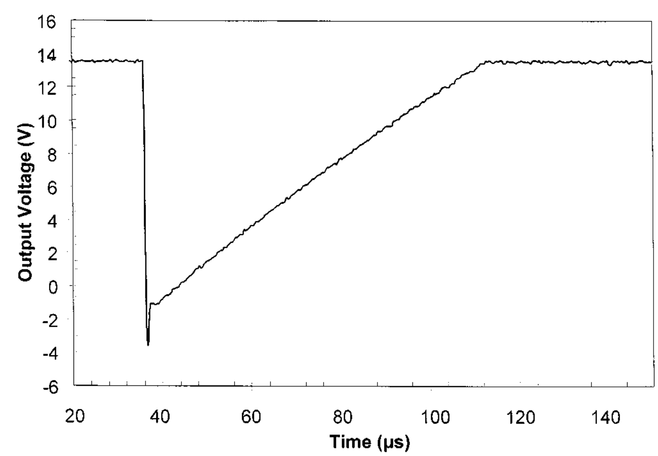

Fig. 12. LM124, voltage comparator application, typical large negative-going transient. Transistor Q12 irradiated with a 64-pJ laser beam, Vcc $= \pm 15$ V, V+ $= 0.05$ V, V− $= 0$ V.

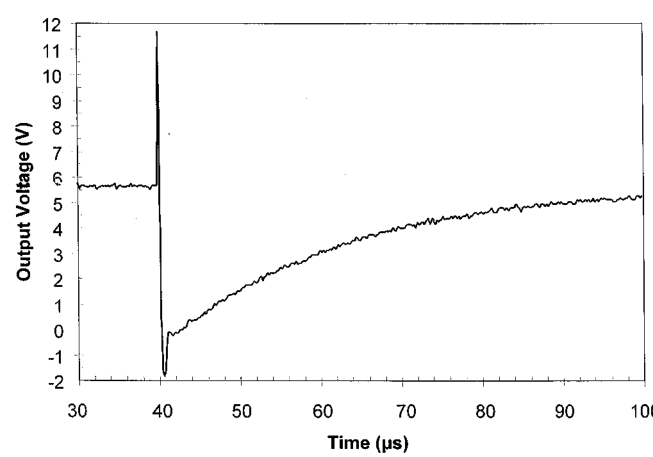

Fig. 13. LM124 noninverting gain application x101, typical bipolar transient. Transistors Q5/Q6 irradiated with a 214-pJ laser beam, Vcc $= \pm 15$ V, V+ $=$ 0.05 V.

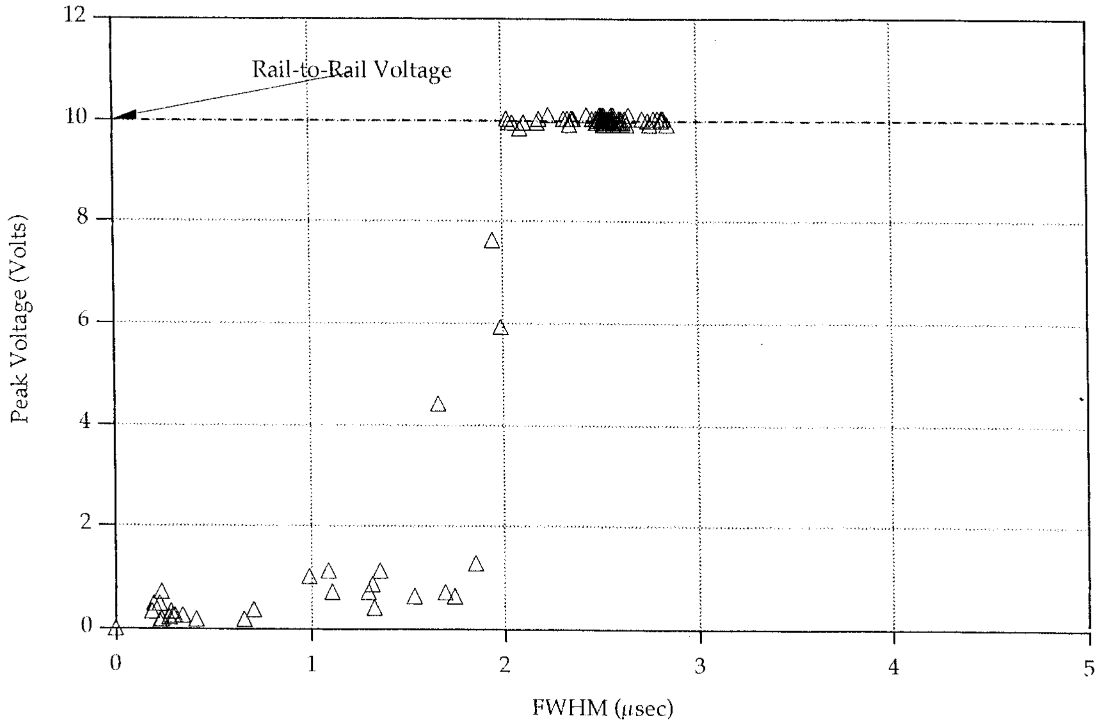

Fig. 14. LM139, example of the pulse characteristics distribution for an irradiation run.

IV. DISCUSSION

Most of the results presented for the LM139/HS139 have already been presented in earlier works [4], [5], [8]. However, no systematic observations had been made on the effect of the power-supply voltage. In addition, we have collected thousands of transients and analyzed every transient characteristic (waveform, voltage amplitude, and FWMH). The objective was to observe the effect of the different parameters on the transient characteristics and to define the worst case transients. An example of the transient voltage amplitude and FWMH obtained during an irradiation run is shown in Fig. 14. All the results obtained are very consistent and show that the most sensitive device regions are the input transistors of the input differential amplifier. When Vin$+ >$ Vin$-$, if the pulse induced by the charge deposited by an ion hitting Q1 or Q2 is of sufficient amplitude and duration, the differential amplifier output changes, the device output transistor Q8 is turned on, and the device output goes very quickly to the lower rail. When the differential amplifier output comes back to its normal state, the output transistor is turned off and the device output returns to the higher rail following an exponential decay depending on the device output load (including pullup resistor and device output transistor capacitance). If the differential input voltage is low, even small amplitude transients (this means low charge deposited by the ions) in the input transistors will cause a transient at the device output, and most of these transients will be large rail-to-rail transients. If the differential input voltage is high, large transients are needed (this means high charge deposited by the ions) in the input transistors to cause a transient at the device output, and most of these transients will be small. The power-supply voltage has a minor effect on the transient voltage amplitude because for the same device output load, it takes more time to go from $+15$ to -15 V than to go from $+5$ to 0 V. Therefore, for low LET values (i.e., low deposited charges) or large input differential voltages (i.e., large noise immunity), the proportion of rail-to-rail transients is lower for the ± 15 V power-supply voltage than for the other power-supply voltage conditions investigated. The worst case transient is a negative-going or positive-going rail-to-rail and saturated transient (FWMH < 3.5 μs). This transient could be obtained with a low δVi (<0.6 V), a high heavy-ion LET (>20 MeVcm^2/mg), or a high laser energy (>10 pJ). It is then possible to bound the worst case response of these devices with a limited number of test parameters.

For the operational amplifiers, the problem is much more complex because there is a broader variety of possible bias conditions and therefore a much larger variety of transient responses. With the LM124, we have tried to guess the transient response for a specific application (noninverting gain amplifier, voltage follower) by circuit analysis from the transient response of the LM124 biased as a voltage comparator, and then to compare the predicted worst case response with the experimental worst case transients.

Surprisingly, the voltage comparator application showed the lowest sensitivity. The laser experiments have shown that the transistors Q1 to Q4 of the input differential amplifier are not sensitive. It is possible that the transient induced by the ions or the laser on these transistors is filtered by the second-stage amplifier of the LM124. If this is the case, the behavior of a faster operational amplifier could be significantly different. The only sensitive areas of the input differential amplifier are the Q8 and Q9 transistors. Transients induced in this region only appear for high LET ions or high-energy laser beam and give a significant contribution to the overall device response. The resulting transients are small long-duration pulses. The long duration of these transients is attributed to the internal compensation capacitor Cc. The other sensitive regions are located in the second-stage amplifier, and the overall device response is dominated by the transients induced in the Q5 and Q6 output transistors.

If the experimental test results on the voltage comparator application did not allow us to predict the worst case response for any kind of application, the data set collected allowed us to define the SET behavior of the LM124. A large variety of transients has been observed with a wide range of pulse heights and varying widths. Most of the transients have positive polarities or are bipolar. Laser testing has shown that some sensitive regions give large negative-going transients, such as those presented by Adell for an inverting gain application [7], but heavy-ion results have shown that these transients represent less than 1% of the overall device response.

The power-supply voltages and the input voltages have an effect on both the device SET sensitivity and the transient's waveform, but this effect is indirect. The closer the output voltage is to a power-supply voltage rail, the lower the sensitivity is. The low effect of the input conditions could be explained by the nonsensitivity of the input stage of the LM124. In all cases, the highest sensitivity has been observed for the ± 15 V power-supply voltages and the lowest input voltages (and so an output voltage further to the power-supply rails).

These results show that extensive testing with a large variety of test parameters and conditions is needed to bound the different responses of the LM124. Additionally, for each test condition, a sufficient number of transients should be collected in order to get all the different types of transients that are possible. Another complexity of SET testing is the large variety of transient waveforms and the wide range of pulse heights and widths. For example, during the voltage comparator application, it has not been possible to capture complete large negative-going transients, because the time base of the oscilloscope was adjusted for the small positive-going transients that represented 99% of the transients. The laser testing has been very useful to define accurately all the different transient waveforms that are possible.

The results also show that the cross-section curves do not fit the effective LET assumptions. As can be seen in Fig. 8, the experimental points obtained with a tilted beam give higher cross-section values than expected. Pease [9] showed that the collection depth for the LM124 is on the order of 30–100 μm for low LET strikes. It is possible that the tilted beam does not have a sufficient range, and therefore the ion LET is not constant during its path through the sensitive volume.

V. CONCLUSION

The data collected under many different operating conditions have allowed the identification of the most important parameters to bound the worst case responses of the three tested devices. These worst case transient waveforms could then be used by space systems' designers in order to assess their criticality in their specific application. For the LM139/HS139 voltage comparators, it is possible with a limited number of experiments to determine the worst case transient. However, for the LM124 operational amplifier, extensive testing with a large variety of test parameters and conditions is needed in order to bound the different worst case responses. A low-cost generic test procedure with a limited number of test conditions is applicable to some, but not all, linear devices.

The test results have also shown the complexity of SET testing with the large variety of transient waveforms and pulse heights and widths that could be obtained. During heavy-ion testing, a sufficient number of transients should be collected in order to collect all the different types of transients that are possible. As the concept of effective LET does not apply for all devices, the use of tilted beam should be avoided for SET testing.

Laser testing has proven to be very useful to identify the different types of SETs that are possible and define accurately the pulse heights and widths.

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